A Biomechanical Analysis of Patellofemoral Stress Syndrome

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ABSTRACT: This study was conducted in order to: a) investigate the relationship of selected anthropometric, strength, and kinematic variables to the incidence of patellofemoral stress syndrome in high school female athletes; and b) develop a predictive equation to screen individuals who may be predisposed to patellofemoral stress syndrome. Twenty-nine subjects were analyzed across nine dependent variables: two anthropometric measures, one strength measure, and six kinematic measures. Heavy subjects and those with a larger static quadriceps angle (Q-angle) were more likely to have patellofemoral stress syndrome. Leg strength did not seem to be a factor. Also, a variable of gait, the time from foot contact to the time when the minimum dynamic Q-angle occurred, was significantly slower in the subjects with patellofemoral stress syndrome. Furthermore, a predictive equation, which we created using discriminant analysis, was 89% accurate in predicting which subjects would or would not have patellofemoral stress syndrome. The equation uses an individual's weight, pelvic width, and static Q-angle. We conclude that, through proper screening, individuals susceptible to patellofemoral stress syndrome may be identified prior to their becoming symptomatic, and that, through identifying causal variables, corrective procedures may be introduced in order to prevent patellofemoral stress syndrome from hindering an individual's physical activity.

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There are many orthopedic problems that require anthropometric and biomechanical scrutiny in order to determine specific causes of pathology. Patellofemoral stress syndrome serves as a prime example, because it is a source of pain and discomfort to many who participate in physical activity. Anterior knee pain occurs most commonly in adolescent females (7,8,24).

Researchers of the etiology of this problem have agreed that there are many potential causes of patellofemoral stress syndrome (10,14,17,20). Past studies (15,26,27,33) have used expensive, noninvasive roentgenographic techniques, as well as invasive surgical procedures, to look at the relationship between the patella and femur. Most of these studies have involved static analysis (5,10,22), internal scrutiny of structural components (25,27), passive dynamic analysis with cadaveric knees (2,16), and clinical observation (3,13,23). From these studies, factors hypothesized to be linked with patellofemoral stress syndrome are: weak vastus medialis obliquus (VMO), large quadriceps angle (Q-angle), increased pronation, shallow femoral sulcus, abnormally shaped patella, hypoplasic lateral femoral condyle, tight lateral retinaculum, variable length and width of the patellar tendon, and tight hamstrings.

For this study we performed functional, dynamic research that would corroborate hypotheses based upon past clinical, static, and passive dynamic studies. The conditions surrounding the biomechanical testing setting were intended to closely approximate the actual circumstances of injury. Observing the resultant movements and using biomechanical techniques, in particular cinematography, allowed us to quantify the variables in question.

Materials and Methods

For the investigation, we selected 44 high school female athletes (age = 16.1 ± 1.3 yr). We divided them into three unequally sized groups. Subjects for Group I, the symptomatic subjects, met the following criteria: (a) no health problems except patellofemoral stress syndrome as diagnosed by a physician, and (b) participation in a high school sport that requires running. Fourteen of the subjects were diagnosed as having either unilateral or bilateral patellofemoral stress syndrome, providing us with 21 symptomatic knees for analysis. Subjects in Group II, the asymptomatic subjects, were healthy high school athletes. This group contained 15 subjects, therefore 30 asymptomatic knees. Group III, the verification subject group was composed of 15 subjects, eight with patellofemoral stress syndrome. They provided us with 14 asymptomatic knees and ten symptomatic knees. Note that the six asymptomatic knees that had contralateral symptomatic knees were not included in the division of this asymptomatic group. Group III was used exclusively for verifying the predictive equations created from Groups I and II.

Based on previous research and for the purpose of the investigation, we identified nine variables (Table 1) related to or descriptive of an individual with patellofemoral stress syndrome. We selected two anthropometric variables, weight and static Q-angle.

We obtained strength data from a Cybex II dynamometer and dual channel

Table 1.—Means, Standard Deviations, and Statistical Comparisons for All Variables

Variable	Asymptomatic Mean (SD)	Symptomatic Mean (SD)	df	t Value	p Value
Weight (N)	515(63)	612(69)	44	4.97	0.001*
Static Q-angle (degrees)	15.2(2.3)	17.1(2.7)	44	2.71	0.01*
Maximum quadriceps strength (Nm/kg)**	2.55(.37)	2.45(.40)	44	.83	0.21
Maximum pronation (degrees)	12.0(3.4)	12.3(3.5)	44	.40	0.39
Time to maximum pronation (s)	0.094(.021)	0.106(.021)	44	1.78	0.04
Velocity at maximum pronation (degrees/sec)	166.1(46.5)	134.8(49.5)	44	2.21	0.02
Minimum dynamic Q-angle (degrees)	9.5(4.2)	7.1(4.3)	44	1.78	0.04
Time to minimum dynamic Q-angle (a)	0.099(.02)	0.127(.025)	44	4.03	0,001*
Q-angle at maximum pronation (degrees)	10.9(3.9)	8.5(3.9)	44	2.01	0.025

*Significant at 0.01 level
**Strength as a ratio of peak torque to body weight

recorder. We recorded concentric knee extension and flexion torques for each individual performing at 60° per second throughout the full range of motion. We normalized the strength data by dividing the torque by the subject's body mass in kilograms resulting in Nm/kg. For the testing procedure, we gave standardized instructions and tested subjects using the protocol as presented in the Cybex II test manual (19). We evaluated peak torque values representing maximum quadriceps strength for each subject in Groups I and II.

Using two electronically driven Photo Sonic Dl-PL, 16mm cameras while the subjects ran on a Quinton Model 18-60 treadmill, we collected cinematographic data. Cameras were placed 6.10m directly in front of and 6.10m directly behind the subjects. The cameras filmed active, dynamic Q-angle anteriorly, and rearfoot motion posteriorly. A nominal film speed of 100 Hz was used. It was calibrated at 99.8 Hz using the number of pulses generated by an internal LED timing light. Both cameras were equipped with Angenieux 12 to 120mm zoom lenses, shutter factors of 90/360, and f/stops of 1.8. We calibrated the treadmill for accurate speed prior to filming, and ran it at a 3.5 m/sec pace for all subjects.

Once on the treadmill, subjects walked at a 1.2 m/sec pace for a short acclimation period, approximately 30 seconds, then the speed was increased in five equal increments of 0.46 m/sec until the subjects reached the test speed. The speed was increased after subjects told us that they were comfortable on the treadmill. Total time on the treadmill for each subject averaged seven minutes. After subjects were comfortable at the test speed, we filmed five right and five left consecutive footfalls.

We used a NAC Analysis Projector DF 16C to view and mark the frames to be studied. The two film records were synchronized using the frames of foot contact. All trials that were analyzed had equal numbers of frames in both anterior and posterior film records indicating identical film speeds in both cameras.

The following body points were digitized with a Vanguard M-16C projector motion analyzer and a SAC Graf/Pen GP-8 sonic digitizer: (a) a mark on the running shorts representing the anterior superior iliac spine, the midpoint of the patella, and the tibial tubercle for the front view, and (b) two points on a line segment bisecting the lower leg and two points on a line bisecting the calcaneus (Fig 1, Fig 2) for the rear view. Three footfalls for both lower extremities were digitized for each subject. Selection of footfalls was based upon ease of recognition of landmarks for digitizing. Each point was digitized three times, visually checked for outlying values, and averaged to provide greater reliability. Each trial was digitized from the frame before

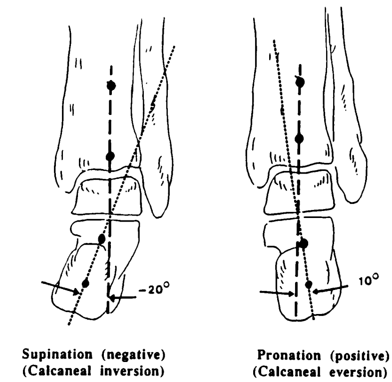

Fig 1.—Rearfoot markings (right leg); pronation and supination

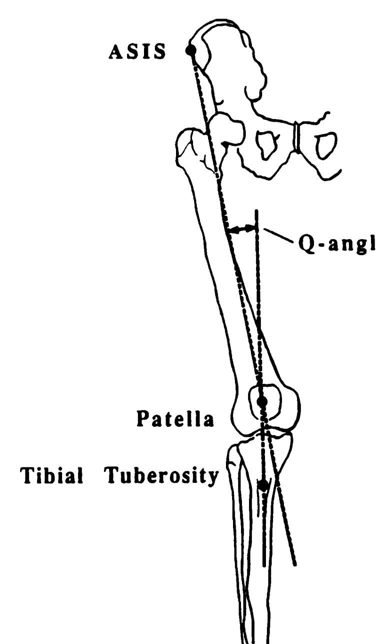

Fig 2.—Quadriceps angle (Q-angle) markings

heel strike to the frame of toe off. The resultant data were smoothed with an interactive routine (35).

We calculated the Q-angle, pronation angle, and angular velocities from the film data. Also, six variables describing Q-angle and pronation were calculated from the film: (a) maximum angle of pronation, (b) time to maximum pronation, (c) average velocity of pronation from rearfoot contact to maximum pronation, (d) minimum dynamic Q-angle, (e) time to minimum dynamic Q-angle, and (f) dynamic Q-angle at the time of maximum pronation.

We used student t-tests with Bonferroni comparisons ($p<0.01$) to compare the mean values for the variables between Groups I and II. Using discriminant analysis techniques (30), we formulated three predictive equations on: (a) practically quantified independent variables (weight, pelvic width, static Q-angle), which are easily measured using simple hands-on techniques; (b) technically quantified independent variables (quadriceps strength, maximum pronation, minimum dynamic Q-angle), which are measured using isokinetic strength testing equipment, high speed cinematography, and computer analysis; or (c) a combination of the practical and technical variables used in the two previously mentioned equations. The discriminant analysis was performed on Groups I and II, and verified with an independent group, Group III.

Results

Data from Groups I and II are in Table 1. Weight and static Q-angle were significantly greater ($t(44)=4.97$, $p=.001$ and $t(44)=2.71$, $p=.01$) in the symptomatic group. A 97 N (19%) difference in weight and a 1.9° (12%) difference in static Q-angle indicated that the subjects with patellofemoral stress syndrome were heavier and had a greater valgus angle at the knee. None of the strength characteristics were significantly different.

One kinematic variable was significantly different ($t(44)=4.03$, $p=.001$) between the two groups. It took 28% longer for subjects with patellofemoral stress syndrome to reach their minimum dynamic Q-angle from foot contact than it took for asymptomatic subjects.

The first predictive equation consisted of three variables that could be measured quickly and easily (Table 2). It could predict 89% of the time whether a subject would or would not have patellofemoral stress syndrome. The second equation used three variables that had to be measured by Cybex dynamometry, high speed cinematography, and computer analysis. This equation did not perform as well. It correctly predicted 71% of those who were not symptomatic and 56% of those who were symptomatic. The third equation consisted of all six variables from the two previously mentioned equations. It correctly predicted 93% of those who did not have patellofemoral stress syndrome and 72% of those who did. A verification group consisting of 15 subjects was used to determine the predictability of the best discriminant equation. The first equation was deemed the best, because it had an overall higher predictive ability than the other equations, and obtaining values for the equation's variables was simple.

Table 2.—Discriminant Analyses

Function	Actual Group	Predicted Group Asymp	Predicted Group Symp	Overall Predictability
Practical Variables*	Asymp = 28	25 (89%)	3 (11%)	89%
	Symp = 18	2 (11%)	16 (89%)	
Technical Variables**	Asymp = 28	20 (71%)	8 (29%)	65%
	Symp = 18	8 (44%)	10 (56%)	
Combined Variables†	Asymp = 28	26 (93%)	2 (7%)	85%
	Symp = 18	5 (28%)	13 (72%)	
Verification Variables††	Asymp = 14	10 (71%)	4 (29%)	79%
	Symp = 10	1 (10%)	9 (90%)	

* Practical variables function is 0.124 static Q-angle - 64.2 pelvic width + 0.026 weight + 3.3.

** Technical variables function is 0.23 minimum dynamic Q-angle - 2.01. The values for maximum pronation and maximum quadriceps strength did not meet the entry criteria for use in this equation.

† Combined variables function is 0.16 static Q-angle - 64.8 pelvic width + 0.025 weight - 0.11 minimum dynamic Q-angle + 4.24.

†† Verification variables function uses the practical variables function with data from the verification group.

Discussion

Anthropometric variables that were significant in this study correspond to those reported in previous research. Heavier runners produce larger ground reaction forces (12), and there is a direct relationship between ground reaction forces and joint reaction forces and moments (34). Therefore, the heavier symptomatic subjects in this study probably had larger forces and moments about the knee. In order to control these large forces, the quadriceps must contract eccentrically, exerting a large force so that a controlled, smooth running gait can occur. Because the patella acts as a fulcrum for, and is embedded in, the quadriceps mechanism, it also will undergo large forces that will predispose it to injury (9).

The larger value for static Q-angle observed in the symptomatic knees agrees with that of Aglietti et al. (1), who reported that static Q-angles greater than 17° are associated with patellofemoral stress syndrome and that asymptomatic knees have smaller static Q-angles of 15°. The difference of 1.8° between groups appears to be small, but must be considered in the context of chronic, or overuse, injury development. Namely, running and jump training involve numerous repetitions of knee flexions and extensions and ground contact phases.

Over the course of several months, small differences between single steps may have a cumulative effect. This effect holds true for small impact forces repetitively applied to animal legs (28). Joint degeneration and changes in substance of subchondral bone and articular cartilage were observed. The critical variable alluded to by the data in this study seems to be the Q-angle. This idea is supported by those subjects who displayed symptoms in one knee. The weight was the same over both knees, but the knee with the larger Q-angle was more likely to have patellofemoral stress syndrome. For example, subject ten was asymptomatic in the right knee and had a static Q-angle of 12° on that side. The contralateral, symptomatic knee had an angle of 16°.

The strength variables were not significantly different. This result does not substantiate the prevailing thought that quadriceps weakness, particularly in the vastus medialis obliquus is largely the responsible component of patellofemoral stress syndrome (11,24). We believe that our strength measures were not significant, because they were concentric measurements. The main function of the quadriceps, when running or landing from a jump, is to decelerate the fall of the body's center of mass, an eccentric action (17). Recommendations for further study include eccentric strength analyses of the quadriceps, which may show differences between Groups I and II.

Kinematic variables that we analyzed reflected pronation and Q-angle movements. Elapsed time to reach minimum Q-angle was significantly smaller in the asymptomatic group. This follows the pattern of a nonpathological closed kinetic chain whereby, when maximum pronation is reached more quickly, concurrent dynamic Q-angle should respond similarly. Many (6,31,32) consider patellofemoral stress syndrome to be primarily the result of an asynchronous closed kinetic chain, particularly in the relationship of rearfoot pronation to quadriceps angle.

Elements of pronation deemed critical by physicians and biomechanists (5,18,21, 29) are the total degrees pronation and the time during which pronation takes place. These areas influence the shock-absorbing ability of the foot and leg. Velocity at maximum pronation was not significantly larger in the asymptomatic group, but the slower value in the symptomatic group did make us think that it may have been a factor in the development of patellofemoral stress syndrome. Because pronation is crucial to decreasing the forces at foot contact, if the velocity at which pronation occurs is high enough, the dissipation factors may not be able to accommodate the vertical ground reaction forces of the movement; hence, trauma occurs to structures not normally responsible for absorbing such forces.

The value of the dynamic Q-angle which coincided with maximum pronation is interesting. Tiberio (32) alluded to the closed kinetic chain relationship between pronation and Q-angle, and stated that as the foot pronates, the tibia internally rotates, which effectively causes the Q-angle to become smaller. Theoretically, the point during footfall when maximum pronation occurs should be where the minimum Q-angle occurs. When the foot begins supination, the tibia should respond by externally rotating, resulting in progressively larger Q-angles, as dictated by normal kinematics (4,31). If these events do not occur simultaneously, rotational moments in opposite directions will result at the subtalar joint and at the articulations of the tibia, femur, and patella. The resultant counterrotational torques will manifest themselves somewhere along the kinetic chain, with a probable site being the knee. It should be noted that dynamic Q-angles were measured in two dimensions in this study and that other rotational components may affect these measurements. This is a limitation of the study.

We believe the first discriminant equation was best because it used variables that were less cumbersome and less costly to measure, and it was a better predictor than the others. Also, athletic trainers and others who see athletes prior to competitive seasons can easily advise the athletes based on the outcome of these simple variable measurements. Including weight as a variable was the major factor in producing a good predictor. The mean values of weight for the asymptomatic group and symptomatic group differed substantially. It should be noted that the practical variables were equally adept predictors for the asymptomatic group (89%) and for the symptomatic group (89%). The verification subjects displayed a different trend, with symptomatic subjects being predicted correctly at a higher rate than nonsymptomatic subjects (90% to 71%).

Prevention of athletic trauma via appropriate screening activities is imperative. Our research takes an important step in that direction using anthropometric, isokinetic, and biomechanical techniques. It is interesting that the practical variable equation using only anthropometric variables had the highest prediction ability and was the least cumbersome to use, making it applicable in the clinical setting. As obvious as it seems, those individuals who are heavier should probably be encouraged to lose weight prior to engaging in athletics that require a lot of running and jumping. Or, they should be advised to participate in activities such as walking, biking, swimming, and low impact aerobics, because these do not require vertical ground forces.

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References

1. Aglietti P, Insall JN, Cerulli G. Patellar pain and incongruence. *Clin Orthop.* 1983; (176): 217-223.
2. Ahmed AM, Burke DL, Hyder A. Force analysis of the patellar mechanism. *J Orthop Res.* 1987; 5(1): 69-85.
3. Antich TJ, Randall CC, Westbrook RA, Morrissey MC, Brewster CE. Evaluation of knee extensor mechanism disorders: clinical presentation of 112 patients. *J Orthop Sports Phys Ther.* 1986; 8(5) 248-254.
4. Brody DM. Running injuries. *Clin Symp.* 1980; 32(4): 1-36.
5. Buchbinder MR, Napora NJ, Biggs EW: The relationship of abnormal pronation to chondromalacia of the patella in distance runners. *J Am Podiatr Assoc.* 1979; 69(2): 159-162.
6. D'Amico JC, Rubin M: The influence of foot orthoses on the quadriceps angle. *J Am Podiatr Med Assoc.* 1986; 76(6): 337-340.
7. DeHaven KE, Lintner DM. Athletic injuries: comparison by age, sport, and gender. *Am J Sports Med.* 1986; 14(3): 218-224.
8. Eisele SA: A precise approach to anterior knee pain. *Phys Sportsmed.* 1991; 19(6): 126-139.
9. Ekholm J, Nisell R, Arborelius UP, Hammerberg C, Nemeth G. Load on knee joint structures and muscular activity during lifting. *Scand J Rehabil Med.* 1984; 16(1): 1-9.
10. Ficat RP, Hungerford DS. *Disorders of the Patellofemoral Joint.* Baltimore: Williams and Wilkens; 1977: 107-143.
11. Fisher RL. Conservative treatment of patellofemoral pain. *Orthop Clin North Am.* 1986; 17(2): 269-272.
12. Frederick EC, Hagy JL. Factors influencing peak vertical ground reaction forces in running. *Int J Sports Biomech.* 1986; 2: 40-41.
13. Garrick JG. Anterior knee pain. *Phys Sportsmed.* 1989; 17(1): 75-84.
14. Goodfellow J, Hungerford DS, Zindel M. Patellofemoral joint mechanics and pathology: 1. functional anatomy of the patellofemoral joint. *J Bone Joint Surg.* 1976; 58B(3): 287-290.
15. Hejgaard N, Diemer H. Bone scan in the patellofemoral pain syndrome. *Int Orthop.* 1987; 11(1): 29-33.
16. Huberti HH, Hayes WC. Patellofemoral contact pressures. *J Bone Joint Surg.* 1984; 66A(5): 715-724.
17. Hughston JC, Walsh WM, Puddu G. *Patellar Subluxation and Dislocation.* Philadelphia: Saunders; 1984: 1-13,157-171.
18. James SL, Bates BT, Osternig LR. Injuries to runners. *Am J Sports Med.* 1978; 6:40-50.

19. Lumex Inc. *Isolated Joint Testing and Exercise: A Handbook for Using Cybex II.* Ronkonkoma, NY: Cybex; 1985: 18-21.
20. Moskwa CA, Nicholas JA. Musculoskeletal risk factors in the young athlete. *Phys Sportsmed.* 1989; 17(11): 49-59.
21. Moss RI. *A Biomechanical Analysis of Patellofemoral Stress Syndrome.* Carbondale, IL: Southern Illinois University; 1989. Doctoral Dissertation.
22. Percy EC, Strother RT. Patellalgia. *Phys Sportsmed.* 1985; 13(7): 43-59.
23. Pretorius DM, Noakes TD, Irving G, Allerton, K. Runner's knee: what is it and how effective is conservative management? *Phys Sportsmed.* 1986; 14(12): 71-81.
24. Radin EL. Anterior knee pain. *Orthop Rev.* 1985; 14(3): 33-39.
25. Reider B, Marshall JL, Ring B. Patellar tracking. *Clin Orthop.* 1981; (157): 143-148.
26. Shellock FG, Mink JH, Deutsch A, Fox JM. Kinematic magnetic resonance imaging for evaluation of patellar tracking. *Phys Sportsmed.* 1989; 17(9): 99-108.
27. Siegel MG, Sigueland KA, Noyes FR. The use of computerized thermography in the evaluation of nontraumatic anterior knee pain. *Sports Med.* 1987; 10(5): 825-830.
28. Simon SL, Radin EL, Paul IL, Rose, RM. The response of joints to impact loading—II. In vivo behavior of subchondral bone. *J Biomech.* 1972; 5: 267-272.
29. Slocum DB, James SL. Biomechanics of running. *JAMA.* 1968; 205(11): 704-721.
30. SPSS, Inc. *SPSS - X user's guide.* 3rd ed. Chicago: SPSS, Inc.; 1988: 455-479.
31. Subotnick SI. The biomechanics of running: implications for the prevention of foot injuries. *Sports Med.* 1985; 2(2): 142-153.
32. Tiberio D. The effect of subtalar joint pronation on patellofemoral mechanics: a theoretical model. *J Orthop Sports Phys Ther.* 1987; 9(4): 160-165.
33. Van Eijden TMGJ, Kouwenhoven E, Verburg J, Weijs, WA. A mathematical model of the patellofemoral joint. *J Biomech.* 1986; 19(3): 219-229.
34. Winter DA. Kinematic and kinetic patterns in human gait: variability and compensating effects. *Hum Mov Stud.* 1984; 3: 51-76.
35. Wood GA. Data smoothing and differentiation procedures in biomechanics. In Terjund K, ed. *Exercise and Sports Sciences Reviews.* Philadelphia: Franklin Institute Press; 1982: 308-362.